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## BRIEF OUTLINE OF RESEARCH FINDINGS (4/1/93-1/31/95)

### OVERVIEW

Several innovative millimeter-wave devices have been developed and successfully tested during the period of performance last year. Our research emphasis has been on harmonic devices in order to reduce the magnetic field required by high performance gyrotron sources. (1) A revolutionary new device, the gyrofrequency multiplier, which can potentially generate 50 kW at 1-2 THz by using a 140 GHz gyrotron as its input source, has been tested in our laboratory. The recent experiment generated 3.5 kW at the sixth-harmonic with a conversion efficiency of 4.5% and an upgrade sixth-harmonic experiment has been planned to produce 150 kW with 30% efficiency. (2) Our second-harmonic gyro-TWT amplifier yielded extremely good results. It generated a record-setting output power of 207 kW, with 13% efficiency, 16 dB saturated gain, 2% bandwidth and was completely stable. Its design was based on our Marginal Stability Design Procedure (MSDP) for stabilizing high power gyro-TWTs and our theory that harmonic gyro-TWTs are capable of significantly higher power because the stronger fundamental-harmonic interaction restricts the beam current to low levels for stability. This concept has been extended to design a stable 1 MW, 140 GHz, third-harmonic gyro-TWT amplifier that requires a magnetic field of only 17 kG. (3) The MSDP was also used to design stable high-performance, 35 GHz and 95 GHz, CW TE<sub>01</sub> gyro-TWT amplifiers. The TE<sub>01</sub> mode is extremely attractive because of its low Ohmic dissipation. (4) We have also begun a major new program to develop high power, ultra-wideband prebunched FELs for radar applications. The short-pulse photoemitted electron beamlets from an rf linac cavity and a fast laser will efficiently emit throughout the millimeter range in a resonant FEL wiggler if the electron bunch length is less than the rf wavelength. The table-top uv laser has been partially tested and a high power, state-of-the-art X-Band klystron has been acquired from SLAC. A compact, light weight design utilizing a standard X-Band magnetron has also been developed. (5) We have continued to construct a high-performance 250 kW, 33.2 GHz TE<sub>01</sub>/TE<sub>02</sub> gyroklystron amplifier. In addition, we have also planned an experiment to test our 70 kW, 95 GHz, third-harmonic, smooth-bore gyroklystron design, which is a much more robust structure than the slotted third-harmonic gyroklystron being built by Litton under ARPA's fast-wave amplifier program.

#### A. High Harmonic Gyrofrequency Multiplier

A revolutionary new concept for the efficient production of high power millimeter and submillimeter wave radiation, which was conceived by our group, has been successfully tested in a second proof-of-principle experiment. A gyrofrequency multiplier emits at a high harmonic of the cyclotron frequency, making it possible to operate with significantly reduced magnetic fields and to multiply the frequency of existing high-power microwave sources. As shown in Fig. 1, in the input

cavity, low frequency microwaves tuned to the cyclotron frequency accelerate and bunch an electron beam, which then emits at a high harmonic of the cyclotron frequency in the output cavity with all electrons optimally phased to give up energy, resulting in extremely high efficiency. Our initial proof-of-principle experiment in 1988 at the third harmonic resulted in the generation of 7 kW at 28 GHz with 13% efficiency.

The goals of our recent experiment were to significantly increase the harmonic number, power level and efficiency of our pioneering proof-of-principle experiment. By converting a 2.9 GHz input signal to 17.4 GHz, the sixth-harmonic gyrofrequency multiplier generated 3.5 kW with a conversion efficiency of 4.5%. The sixth-harmonic gyrofrequency multiplier whose experimental parameters are shown in Table 1 had been designed by using a simulation code and, as can be seen in Fig. 2, the results are in fairly good agreement with the predictions. The discrepancy can be accounted for by beam loading effects in the output cavity. A self-consistent linear gyrotron code predicts that the frequency shift from the beam is approximately equal to the 3 dB width of the resonant mode, which results in nearly perfect agreement in Fig. 2 between the experiment and simulation by changing  $Q_L$  by two. To replace the cavity and thereby avoid beam-loading, a traveling wave interaction circuit is being constructed for the sixth-harmonic upgrade experiment, which is predicted to produce 150 kW with 30% efficiency.

Much higher power gyrofrequency multipliers will later be experimentally investigated using our 20 MW, 8.6 GHz SLAC klystron to generate radiation in the 86-172 GHz region at harmonics from ten to twenty with power levels up to 2 MW. Eventually, we intend to build a tenth-harmonic multiplier to convert the 1 MW output of a 140 GHz gyrotron into 50 kW of 1.4 THz power.

## **B. High-Power $n^{\text{th}}$ -Harmonic $TE_{n1}$ Gyro-TWT Amplifiers**

Gyro-TWT amplifiers offer high average power at high frequency, but have historically displayed poor stability. Our group has been successful in developing the gyro-TWT into the stable, high-performance amplifier that it was initially envisioned to be. Using the MSDP design procedure that considers the threshold conditions for the various types of oscillation, we have recently built and tested two stable high-performance gyro-TWT amplifiers: a wideband gyro-TWT that displayed a constant-drive bandwidth of 11% and a third-harmonic slotted gyro-TWT designed for operation at 94 GHz in collaboration with Varian Associates.

In addition, in our ARO-funded program, we have developed and tested an extremely high power, smooth-bore, second-harmonic gyro-TWT. Harmonic gyro-TWT's not only require a substantially weaker magnetic field and offer nearly the same high efficiency as fundamental gyro-TWT's, but also can generate significantly higher power levels. Basically, since harmonic interactions are weaker than the fundamental interaction, the start-oscillation beam current is raised significantly. A feature of our  $n^{\text{th}}$ -harmonic  $TE_{n1}$  gyro-TWT's is that the stronger first-harmonic

interaction cannot occur, since the fundamental cyclotron resonance line does not intersect the lowest order mode as seen in Fig. 3.

Our second-harmonic gyro-TWT amplifier (see Table 2) used an 80 kV, 20 A MIG electron gun and generated a record-setting output power of 207 kW. That the highest output power from a stable first-harmonic gyro-TWT is only 120 kW is verification of our claim that harmonic gyro-TWTs can stably generate higher power. Additionally, our device's characteristics included an efficiency of 13% efficiency, 16 dB saturated gain, 2% bandwidth (see Fig. 4) and was completely stable without any rf input power drive. The amplifier's transfer curve (see Fig. 5) shows well-behaved linear and saturated nonlinear regions and confirms the theoretical prediction that the growth rate is proportional to the cube root of the beam current. For detuned, higher gain conditions, our gyro-TWT was stable for gains as high as 39 dB as shown in Fig. 6. The amplifier's excellent stability is due to the well matched circuit components. The overmoded TE<sub>21</sub> input/output directional coupler had been designed with the Hewlett-Packard HFSS 3-D electromagnetics design code. The measured coupling data are in excellent agreement with the HFSS predictions as shown in Fig. 7. All modes are well terminated in this coupler with a return loss of >20 dB over a 20% bandwidth, which is crucial for the amplifier's stability. The entire device was built as a sealed-off demountable tube.

The above concept has been extended to design a higher power, 140 GHz, third-harmonic TE<sub>31</sub> gyro-TWT amplifier. The device described in Table 3 employs a 100 kV, 50 A MIG gun and is predicted by a simulation code to generate 900 kW with 18% efficiency, 30 dB saturated gain and a bandwidth of 6% as shown in Fig. 8. Its stability is ensured by limiting the length of the interaction section to the shortest gyro-BWO start-oscillation length. The 1 MW, 140 GHz, third-harmonic gyro-TWT amplifier would require a magnetic field of only 17 kG. A scaled device in a 50 kG magnet would generate 400 GHz.

### C. Overmoded Gyro-TWT Stability--95 GHz Multi-Section TE<sub>01</sub> Gyro-TWT

We also employed the MSDP procedure to design high-performance 35 GHz and 95 GHz gyro-TWTs using the TE<sub>01</sub> mode, which offers low ohmic dissipation and a favorable interaction strength. Linear theory has been used to determine the threshold conditions for harmonic gyrotron and gyro-BWO oscillation in all waveguide modes. Using interaction sections shorter than the threshold oscillation length and separated by attenuating severs for isolation, a stable three-section amplifier has been designed (see Table 4) that is predicted by a simulation code to yield 105 kW at 94 GHz with 21% efficiency, 45 dB saturated gain and 5% constant-drive bandwidth (see Fig. 9) for a 100 kV, 5 A electron beam. The 35 GHz design with a 10 A beam is predicted to yield 230 kW with 23% efficiency. In addition, the 0 dB quad-feed input/output couplers (see Fig. 10) and an appropriate MIG electron gun has been designed with 2.4% axial velocity spread. Due to the low loss of the circular TE<sub>01</sub> mode, this high-performance amplifier can be operated continuously.

#### **D. Short-Pulse Wideband Emission from RF Photocathode Beams**

We have also begun a major new program to develop an innovative, compact rf accelerator system that can be used to generate high power, ultra-wideband millimeter-waves for radar applications. A wavetrain of short-pulse photoemitted electron beamlets from an rf linac cavity and a short pulse ( $\approx 200$  fsec) laser will coherently emit in an FEL wiggler when the electron bunch length is less than the rf wavelength. The electrons are effectively prebunched and the entire beamlet will efficiently radiate.

We have been actively involved in the design and construction of a compact state-of-the-art rf photoinjector capable of accelerating trains (up to 100) of high charge (1 nC), ultrashort ( $< 5$  ps) photoelectron bunches to energies up to 5 MeV with excellent beam quality (emittance  $< 5\pi$  mm-mrad) at a repetition rate of 2.142 GHz (one bunch every fourth rf cycle). Such a device has many potential applications ranging from laser acceleration to chirped-pulse free-electron lasers and ultra-wideband radars. The photoelectron bunches are produced by illuminating a high quantum efficiency ( $> 5\%$ ) Cesium Telluride photocathode with the 200 fs, 0.1 GW frequency-quadrupled UV pulses from an eight-pass bow-tie Ti:Al<sub>2</sub>O<sub>3</sub> laser amplifier that is driven by a low jitter (400 fs) mode-locked AlGaAs quantum-well laser. The simulation codes SUPERFISH and PARMELA are being used to optimize the design of the 1 1/2 cell linac cavity that will be driven by our 20 MW, 8.568 GHz SLAC klystron. We are also beginning studies of a magnetron driven system which would be suitable for transportable and airborne applications.

#### **E. High-Power Smooth-Bore Gyroklystron Amplifiers**

We have also continued the construction of our high-performance 33 GHz TE<sub>01</sub>/TE<sub>02</sub> gyro-klystron amplifier (see Table 5), which is predicted to yield an output power of 250 kW with an efficiency of 39% and a saturated gain of 52 dB as shown in Fig. 11 by using an 80 kV, 8 A electron beam. Because it uses the low loss TE<sub>0n</sub> modes, the wall loading is weak and the device can be operated cw. Most of the major equipment for the experiment have been assembled and tested. We are ready to begin machining the cavities.

In addition, we are planning an experiment to test our 70 kW, 95 GHz, third-harmonic, smooth-bore gyro-klystron design by using the axis-encircling electron beams produced by our gyroresonant rf accelerator cavity. In an ARPA funded program, Litton is developing a third-harmonic gyro-klystron utilizing a slotted waveguide circuit to increase the interaction strength. The purpose of our study is to determine whether more robust smooth-bore waveguide can be used.

An important feature of our proposed smooth-bore third-harmonic TE<sub>311</sub> gyrokystron is that it is stable, because the axis-encircling beam will not interact at the stronger, lower cyclotron harmonic frequencies. The three-cavity third-harmonic gyrokystron (Table 6) is predicted from our gyrokystron simulation code to yield 70 kW with 20% efficiency, 0.2% bandwidth and a saturated gain of 35 dB as can be seen in Fig. 12.

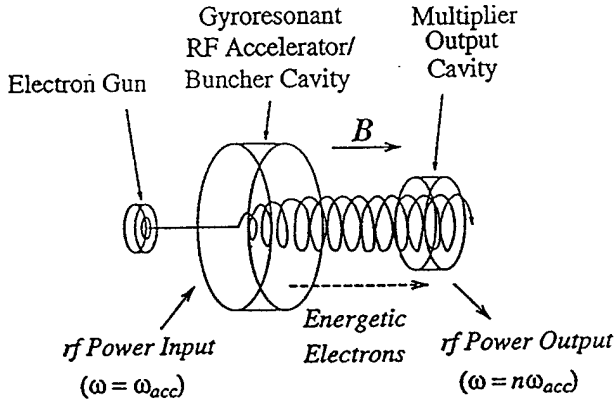


Fig. 1. Schematic of the high-harmonic gyrofrequency multiplier.

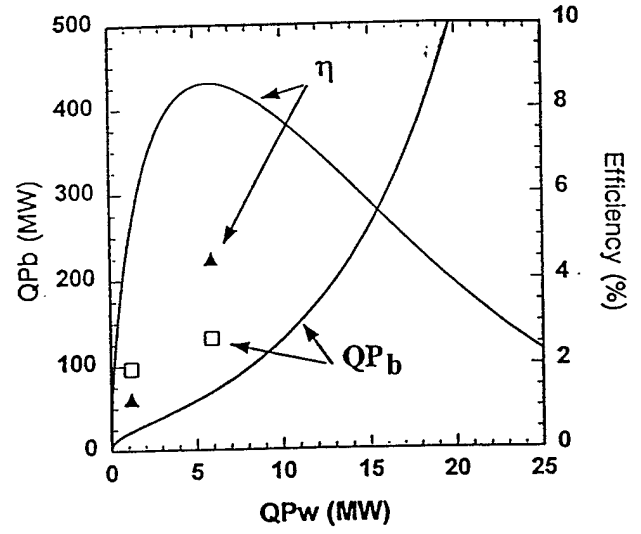


Fig. 2. Dependence of simulated efficiency and beam power times cavity  $Q$  (lines) on wave power times cavity  $Q$  in the gyrofrequency multiplier's output cavity for the experimental beam parameters of Table 1 and compared to the experimental efficiency (triangles) and beam power (squares).

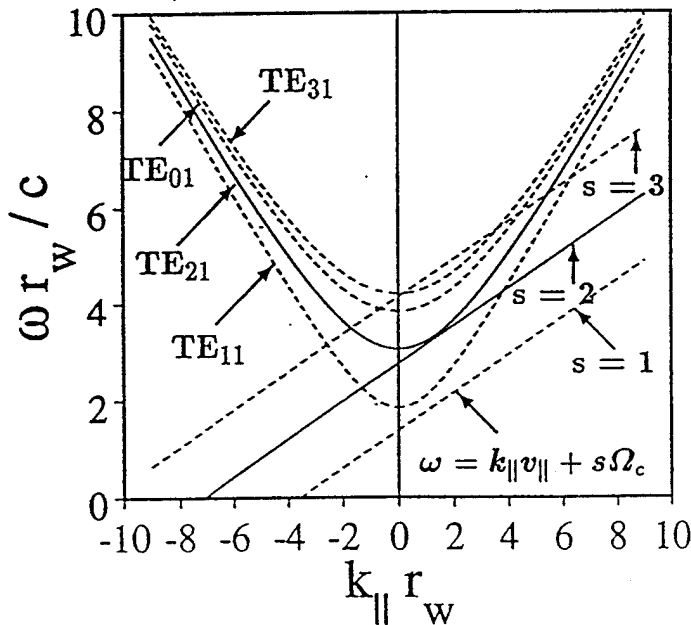


Fig. 3. Uncoupled dispersion relation of operating mode (intersection of unbroken curves) and likely oscillating modes (intersections of broken curves with negative  $k_z$ ) for second-harmonic  $TE_{21}$  gyro-TWT amplifier (100 kV,  $\alpha = 1$ ,  $B_0 = 0.98 B_g$ ).

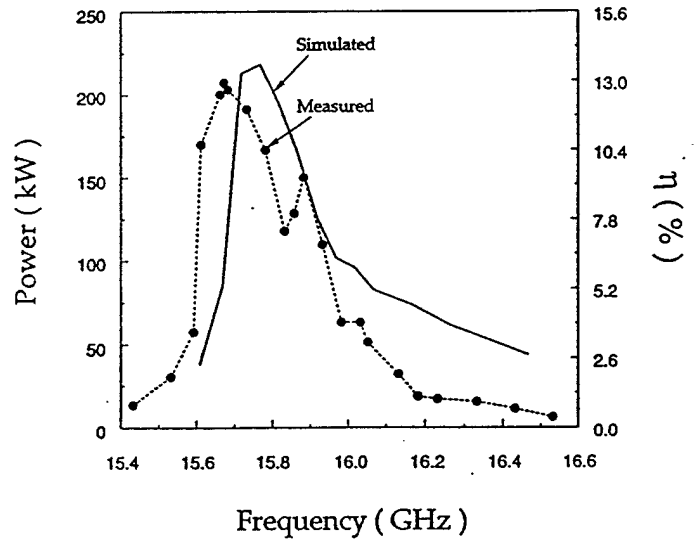


Fig. 4. Measured saturated bandwidth of the second-harmonic  $TE_{21}$  gyro-TWT amplifier showing a peak output power of 207 kW and peak efficiency of 13%. The solid curve represents the simulated results for an 80 kV, 20 A beam with  $\alpha = 1.1$  in a magnetic field of  $B/B_g = 0.97$ .

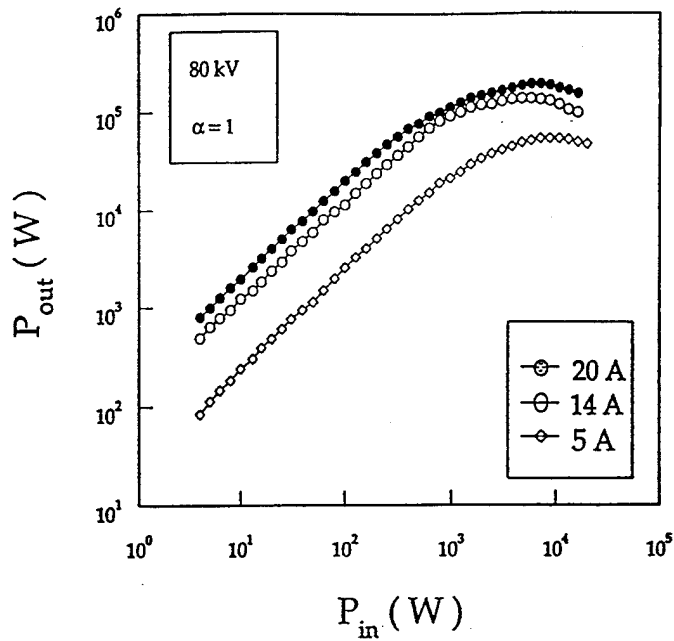


Fig. 5. Measured amplifier transfer curve of second-harmonic TE<sub>21</sub> gyro-TWT for beam currents of 5, 14 and 20 A with the same magnetic field and at the same frequency of 15.7 GHz.

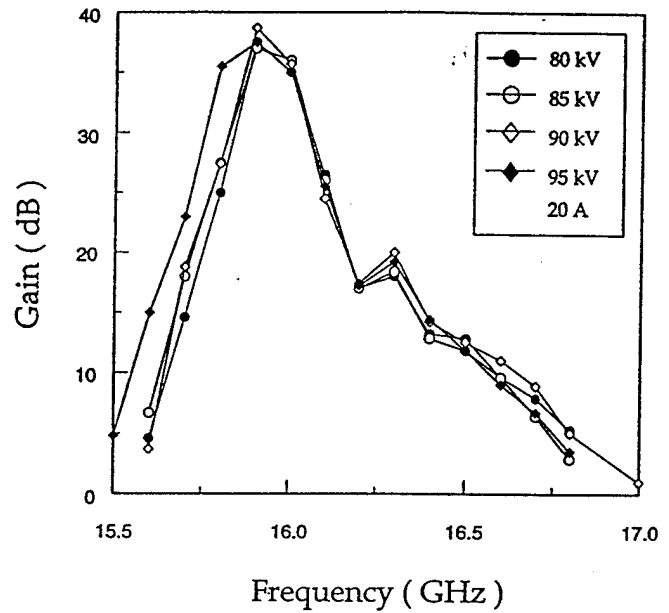


Fig. 6 Measured small signal gain bandwidth for the TE<sub>21</sub> gyro-TWT amplifier with a 20 A beam at different beam voltages (80, 85, 90 and 95 kV).

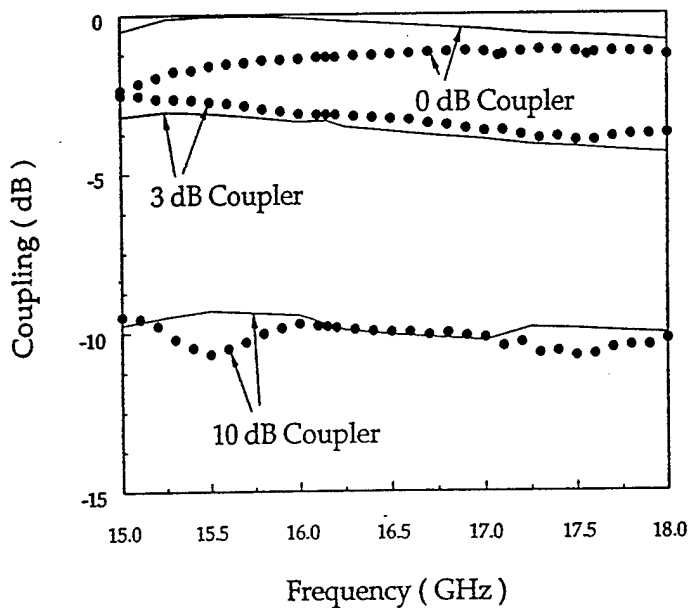


Fig. 7. Performance of 0 dB, 3 dB and 10 dB TE<sub>21</sub> input/output couplers as simulated by HFSS. Solid dots are cold test results.

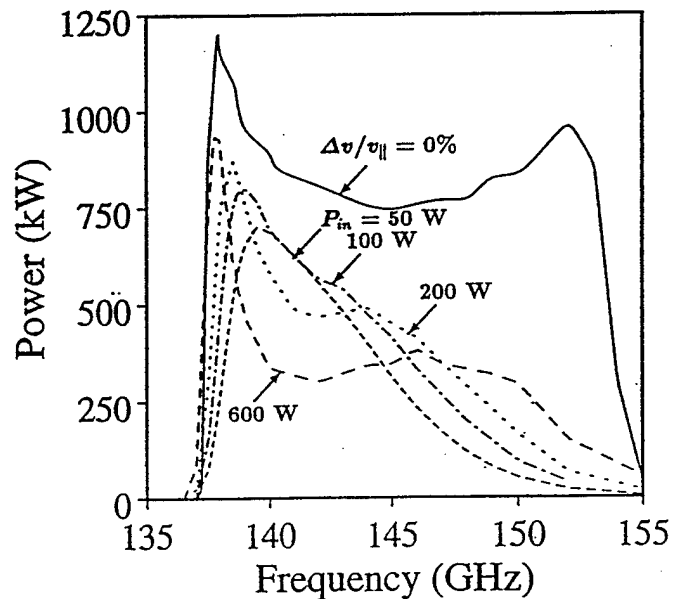


Fig. 8 Bandwidth of proposed third-harmonic single-section TE<sub>31</sub> gyro-TWT amplifier (Table 3) for axial velocity spreads of 0% (solid curve) and 5% (dot and dashed curves).

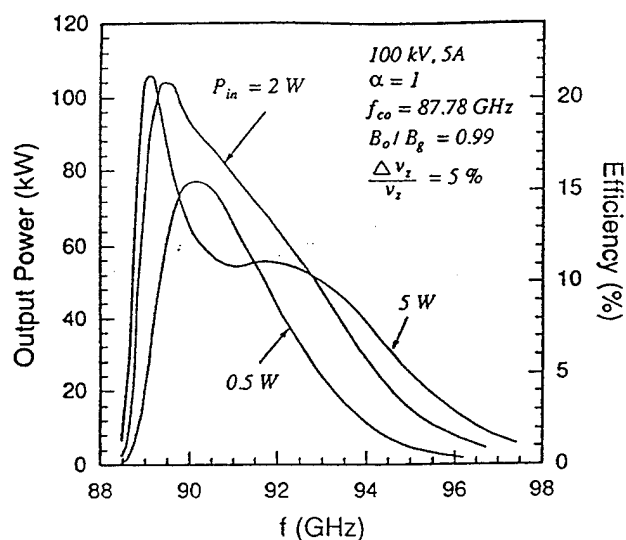


Figure 9. Constant-drive bandwidth for TE<sub>01</sub> gyro-TWT amplifier for three values of input power ( $P_{in} = 1, 6$  and  $12$  W; Table 3).

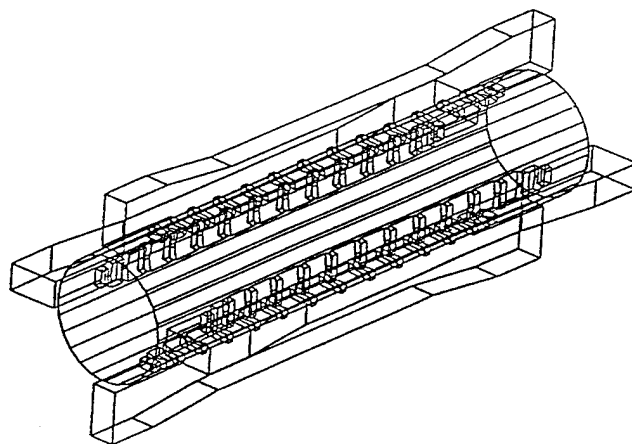


Figure 10. Schematic of rectangular TE<sub>10</sub> to circular TE<sub>01</sub> directional coupler with four rectangular feeds.

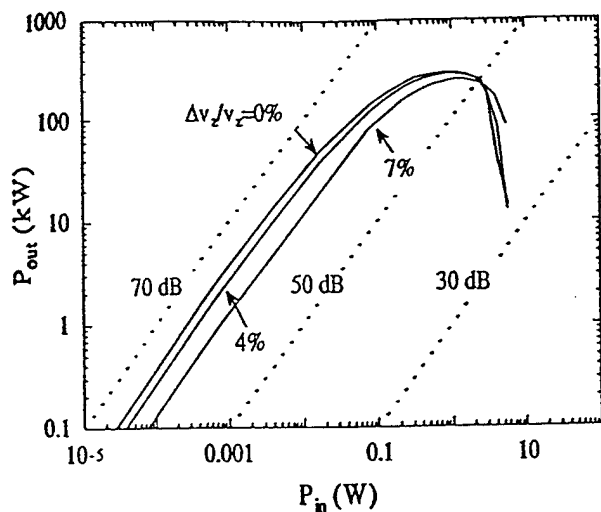


Fig. 11 Gain characteristics of the 33.2 GHz, three-cavity TE<sub>01</sub>/TE<sub>02</sub> gyroklystron amplifier for several values of axial velocity spread.

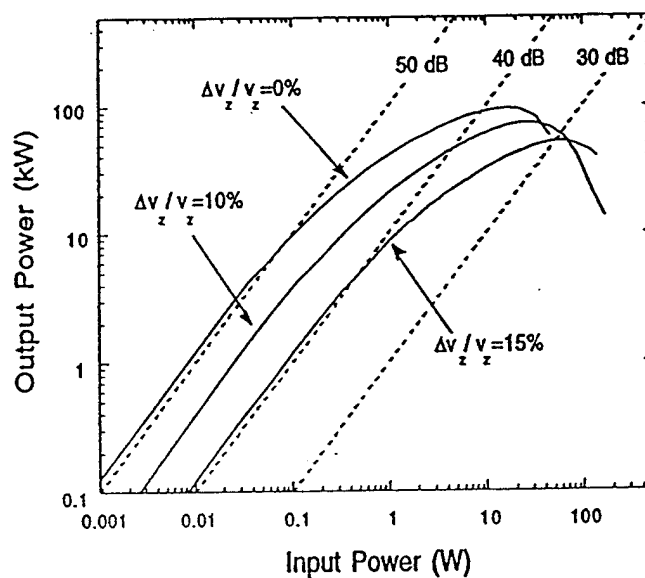


Fig. 12 Gain characteristics of the 95 GHz, three-cavity third-harmonic TE<sub>311</sub> gyroklystron amplifier for several values of axial velocity spread.

## Tables

**Table 1. Experimental Parameters for the Sixth-Harmonic Gyrofrequency Multiplier Experiment.**

|                                  |                   |
|----------------------------------|-------------------|
| Input Power                      | 320 kW            |
| Input Frequency                  | 2.872 GHz         |
| Beam Voltage                     | 260 kV            |
| Beam Current                     | 0.3 A             |
| $\alpha (= v_{\perp}/v_z)$       | 4.8               |
| Guiding-Center Radius            | 0.0 cm            |
| Radial Guiding-Center Spread     | 0.09 cm           |
| Accelerator Cavity Length/Radius | 0.91              |
| Accelerator Cavity Q             | 3200              |
| Accelerator Cavity Mode          | TE <sub>111</sub> |
| Output Cavity Length/Radius      | 4.0               |
| Output Cavity Q                  | 1700              |
| Output Cavity Mode               | TE <sub>612</sub> |
| Magnetic Field                   | 1.50 kG           |
| Magnetic Linear Downtaper        | 2.4%              |

**Table 2. Experimental Parameters for Sliced, Single-Stage, 16 GHz Second-Harmonic TE<sub>21</sub> Gyro-TWT Amplifier with MIG Electron Beam.**

|                            |                  |
|----------------------------|------------------|
| Beam Voltage               | 80 kV            |
| Beam Current               | 20 A             |
| Magnetic Field             | 3.4 kG           |
| Center Frequency           | 15.7 GHz         |
| Cutoff Frequency           | 15.3 GHz         |
| Mode                       | TE <sub>21</sub> |
| Cyclotron Harmonic         | 2                |
| Circuit Radius             | 0.95 cm          |
| $r_c/r_w$                  | 0.4              |
| $\alpha (= v_{\perp}/v_z)$ | 1.1              |
| $B/B_g$                    | 0.97             |
| $\Delta v_z/v_z$           | 14%              |
| $\Delta r_c/r_w$           | 10%              |
| Number of Sections         | 1                |
| Circuit Length             | 65 cm            |

**Table 3. Design Parameters for Single-Section, Sliced, 140 GHz Third-Harmonic TE<sub>31</sub> Gyro-TWT Amplifiers with MIG Electron Beam.**

|                            |                  |
|----------------------------|------------------|
| Beam Voltage               | 100 kV           |
| Beam Current               | 50 A             |
| $\alpha (= v_{\perp}/v_z)$ | 1.0              |
| Magnetic Field             | 17 kG            |
| Center Frequency           | 140 GHz          |
| Mode                       | TE <sub>31</sub> |
| Cyclotron Harmonic         | 3                |
| Circuit Radius             | 0.15 cm          |
| $r_c/r_w$                  | 0.3              |
| $B/B_g$                    | 0.99             |
| $\Delta v_z/v_z$           | 5%               |
| $\Delta r_c/r_w$           | 10%              |
| Number of Sections         | 1                |
| Circuit Length             | 10 cm            |

**Table 4. Design Parameters for High-Performance 94 GHz TE<sub>01</sub> Gyro-TWT Amplifier.**

|                            |                  |
|----------------------------|------------------|
| Center Frequency           | 94 GHz           |
| Beam Voltage               | 100 kV           |
| Beam Current               | 5 A              |
| $\alpha (= v_{\perp}/v_z)$ | 1.0              |
| Magnetic Field             | 34.2 kG          |
| Mode                       | TE <sub>01</sub> |
| Cyclotron Harmonic         | 1                |
| Circuit Radius             | 0.21 cm          |
| $r_c/r_w$                  | 0.5              |
| $B/B_g$                    | 0.99             |
| $\Delta v_z/v_z$           | 5%               |
| Number of Sections         | 3                |
| Section Length             | 3.78 cm          |
| Circuit Length             | 14.2 cm          |

**Table 5. Design Parameters Of TE<sub>01</sub>/TE<sub>02</sub> Three-Cavity Gyro-Klystron Amplifier under Construction.**

|                            |   |
|----------------------------|---|
| Beam Voltage               | 80 kV   |
| Beam Current               | 8 A   |
| $\alpha (= v_{\perp}/v_z)$ | 1.5   |
| Frequency                  | 33.2 GHz  |
| Magnetic Field             | 12.4 kG   |
| Mode (1,2,3)               | TE <sub>011</sub> , TE <sub>011</sub> , TE <sub>021</sub> , |
| Cavity Q (1,2,3)           | 300, 300, 550   |
| Cyclotron Harmonic         | 1   |
| Cavity Lengths             | 2.0 $\lambda$   |
| Drift Tube Lengths         | 3.0 $\lambda$   |
| $\Delta r_c/r_w$           | 10%   |
| $\Delta v_z/v_z$           | 7%  |

**Table 6. Design Parameters for Proposed 95 GHz Three-Cavity, Third-Harmonic Smooth-Bore TE<sub>311</sub> Gyro-Klystron Amplifier with Axis-Encircling Beam.**

|                            |                     |
|----------------------------|---------------------|
| Beam Voltage               | 70 kV               |
| Beam Current               | 5 A                 |
| $\alpha (= v_{\perp}/v_z)$ | 2.0                 |
| Frequency                  | 95 GHz              |
| Magnetic Field             | 12.4 kG             |
| Mode                       | TE <sub>311</sub>   |
| Cyclotron Harmonic         | 3                   |
| Cavity Radii, $r_w$        | 0.21 cm             |
| Cavity Lengths             | 1.26 cm             |
| Cavity Q's                 | 200 (1, 2); 300 (3) |
| Drift Tube Lengths         | 1.26 cm             |
| $\Delta r_c/r_w$           | 10%                 |
| $\Delta v_z/v_z$           | 10%                 |